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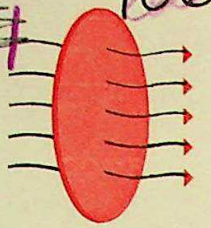

ADOLF MELLER COMPANY
SAPPHIRE PRODUCTS DIVISION

POST OFFICE BOX 702 PROVIDENCE 1, RHODE ISLAND, U. S. A.

SYNTHETIC SAPPHIRE COMPONENTS
WINDOWS • DOMES • LENSES
RODS • TUBES • SPACERS

TEL. DEXTER 1-3717 CABLE ADDRESS: ROSADOLF, PROVIDENCE, (R. I.)

A SUMMARY OF AVAILABLE DATA ON THE PHYSICAL PROPERTIES OF SYNTHETIC SAPPHIRE

R. A. McFARLANE

The physical properties of synthetic sapphire make it valuable for special applications where conventional materials are inadequate. Sapphire has high transmission in the ultraviolet, visible and infrared spectrum and windows can be made which are mechanically strong and wear-resistant. In optical systems the low dispersion of sapphire and its low susceptibility to abrasion make it valuable for outside elements of lenses subject to severe mechanical abuse. A loss of transmission of not more than 3 per cent is encountered when the material is heated to 440°C and transmission properties in the infrared region are useful up to 1,500°C. Sapphire is superior to other infrared transmitting materials which scratch or fracture readily or have high reflection losses.

The low dielectric loss, high resistivity, mechanical strength and freedom from outgassing have led to the use of sapphire for output windows of low and high power microwave tubes, and for insulators and support rods of internal tube structures. The ability of sapphire to make vacuum seals to metal, ceramics, glass, and even sapphire offers many interesting possibilities to the tube designer.

A small amount of chromium added to pure sapphire produces ruby. The paramagnetic resonance of the Cr^{+++} ion in the crystal lattice is used for microwave maser amplifier applications. Available data indicate a resonance bandwidth of approximately 50 Mc/s. for very small amounts of chromium doping, increasing to about 570 Mc/s. with a higher doping of approximately 1 per cent chromium in aluminum sites. The chromium impurity in "pink" ruby is less than 0.1 per cent, in "standard" ruby between 0.1 per cent and 0.5 per cent and in "dark" ruby greater than 0.5 per cent.

Where special applications require accurate crystal orientation, a precision of 0.5° can be achieved by optical methods and 0.01° by X-ray techniques.

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THE PHYSICAL PROPERTIES OF SYNTHETIC SAPPHIRE

Chemical Formula Al_2O_3

Molecular Weight 101.94

Crystal Class Hexagonal system — rhombohedral class

Specific Gravity 3.98

Water Absorption nil

Solubility Sapphire is insoluble in water, and in common acids and alkalis to approximately 1000°C. It is not attacked by HF below 300°C.

Hardness

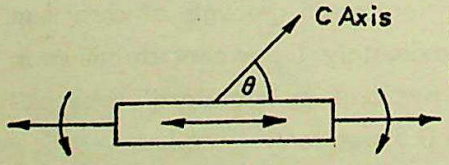
Moh 9

Knoop 1525–2000 depending on orientation.
(1000 gram indenter)

MECHANICAL CONSTANTS

Bulk Modulus 300,000 psi.

Young's Modulus

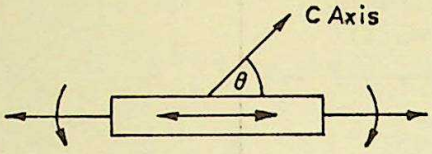


Measurements were made by flexure. The angle indicated is that between the C-axis and the axis of the bar. Values obtained are in general lower than those obtained in either tension or compression.

30° — 5.5×10^7 psi
45° — 5.1×10^7 psi
60° — 5.0×10^7 psi
75° — 5.6×10^7 psi

Modulus of Rigidity This constant was measured in torsion and depends upon crystal orientation. The minimum value quoted is 2.15×10^7 psi.

Modulus of Rupture (Maximum bending stress). This is a function of crystal orientation.



30° — 100,000 psi
45° — 78,000 psi
60° — 65,000 psi
75° — 94,000 psi

THERMAL PROPERTIES

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Melting Temperature 2,040 ± 10°C

Specific Heat 0.0249 @ 91°K
0.1813 @ 291°K

Thermal Expansion Mean Linear Expansion Coefficient over the indicated temperature range with heat flow in the direction indicated.

Temperature	∥ C-Axis	60° to C-Axis	⊥ C-Axis
20°C–50°C	6.66×10^{-6}/°C	5.8×10^{-6}/°C	5.0×10^{-6}/°C
20°C–500°C	8.33×10^{-6}/°C	7.7×10^{-6}/°C	7.70×10^{-6}/°C
20°C–1,000°C	9.03×10^{-6}/°C	8.4×10^{-6}/°C	8.31×10^{-6}/°C
20°C–1,500°C	—	9.0×10^{-6}/°C	—

Thermal Conductivity

The thermal conductivity appears to be little affected by orientation. There is experimental indication that it is very slightly lower along the A-axis (90°) than along the C-axis (0°).

Temperature	Thermal Conductivity cal./(cm. sec. °C)
2.5°K	0.08
4.2°K	0.28
20°K	8.4
35°K	16.
77°K	2.3
200°K	0.21
0°C	0.11
100°C	0.060
300°C	0.039
500°C	0.026
700°C	0.020
900°C	0.018

Heat Capacity

Temperature °K	Heat Capacity Abs. Joules/Deg. Mole
50	2
100	13
200	52
300	79
600	112
900	122
1,200	127

OPTICAL PROPERTIES

Refractive Index — Ordinary Ray, at 24°C.

Wavelength Microns	Refractive Index
0.26520	1.8336
0.28035	1.8243
0.28936	1.8195
0.29673	1.8159
0.30215	1.8135
0.3130	1.8091
0.33415	1.8018
0.34662	1.7981
0.361051	1.7945
0.365015	1.7936
0.39064	1.7883
0.404656	1.7858
0.435834	1.7812
0.54607	1.7708
0.576960	1.7688
0.579066	1.7687

Wavelength Microns	Refractive Index
0.64385	1.7655
0.706519	1.7630
0.85212	1.7588
0.89440	1.7579
1.01398	1.7555
1.12866	1.7534
1.36728	1.7494
1.39506	1.7489
1.52952	1.7466
1.6932	1.7437
1.70913	1.7434
1.81307	1.7414
1.9701	1.7383
2.1526	1.7344
2.24929	1.7323
2.32542	1.7306

Wavelength Microns	Refractive Index
2.4374	1.7278
3.2432	1.7044
3.2666	1.7036
3.303	1.7023
3.3293	1.7015
3.4188	1.6982
3.5078	1.6950
3.70	1.6875
4.258	1.6637
4.954	1.6266
5.1456	1.6151
5.349	1.6020
5.419	1.5973
5.577	1.5864

In the visible region of the spectrum the refractive index for the Ordinary Ray can be written

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$$N_o = 1.74453 + \frac{101.0}{\lambda - 1598},$$

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where λ is the wavelength in angstroms. The refractive index for the Extraordinary Ray is approximately .008 less than that for the Ordinary Ray.

The temperature coefficient of the index of refraction is approximately $+13 \times 10^{-6}$/°C at room temperature for the visible spectrum. It averages $+20 \times 10^{-6}$/°C at the shorter wavelengths and $+10 \times 10^{-6}$/°C near 4 microns.

Reciprocal Dispersion

$$\text{nu value} = \frac{N_D - 1}{N_F - N_C} = 72.2$$

where $\lambda_D = 0.5893\mu$

$\lambda_F = 0.6563\mu$

$\lambda_C = 0.4861\mu$

Optical Transmission

Sapphire has useful transmission from 0.15μ to 6μ. In the visible region losses result primarily from reflection at interfaces. If no internal absorption occurs, the transmittance of a plane-parallel plate can be expressed as a function of the refractive index N,

$$T = \frac{2N}{N^2 + 1} \quad ,$$

where internal reflections are considered.

At wavelengths shorter than 0.3μ internal absorption results in an additional decrease of transmission.

Wavelength Microns	Transmittance of 1 mm. Plate
0.28	79%
0.22	72%
0.20	66%
0.18	53%
0.16	34%
0.15	21%

In the infrared region, transmission is maintained out to approximately 4 microns. At longer wavelengths internal absorption decreases transmission.

Wavelength Microns	Transmittance of .94 mm. Plate
3.0	92%
5.35	84%
6.3	34%

The coefficient of absorption at $\lambda = 5.35$ microns is 1.9 cm.$^{-1}$ and at $\lambda = 6.3$ microns is 7.6 cm.$^{-1}$ Overall transmittance calculations must include Fresnel reflection losses.

$$T = \frac{(1 - r)^2 e^{-\alpha X}}{1 - r^2 e^{-2\alpha X}}$$

where T is the ratio of transmitted to incident light intensity.

r is the surface reflection coefficient given in terms of the refractive index of the window material N.

$$r = \frac{(N - 1)^2}{(N + 1)^2}$$

α is the coefficient of absorption.

χ is the thickness of the window.

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ELECTRICAL PROPERTIES

Volume Resistivity — Indicated values are order of magnitude only.

500°C — 10^{11} ohm/cm.
1,000°C — 10^{9} ohm/cm.
1,500°C — 10^{5} ohm/cm.
2,000°C — 10^{3} ohm/cm.

Te Value

1,231°C parallel to C-axis.
1,214°C perpendicular to C-axis.

Dielectric Strength

480,000 volts/cm.
(60 cycle) 1,200 volts/mil

Dielectric Constant

Temperature	Electric Field Relative to C-Axis	
	Perpendicular	Parallel
20°C	9.35	11.53
100°C	9.43	11.66
300°C	9.66	12.07
500°C	9.92	12.54
700°C	10.26	13.18

The above values are valid for frequencies from 10^4 to 9×10^9 c.p.s. For frequencies below 10^4 c.p.s. the dielectric constant increases slightly with temperature above 400°C. Below 400°C no frequency dependence is apparent.

Loss Tangent

At low frequencies the loss tangent is a very strong function of temperature. Over the audio range it can be represented within a factor of 2 by

$$\tan\delta = \frac{A}{2^{\log_{10}\left(\frac{f}{100}\right)}} 10^{\left[16 - \log_{10}\left(\frac{f}{100}\right)\right]\frac{T}{2000}}$$

where f is the frequency in c.p.s.
T is the temperature in °C.

$A = 2.4 \times 10^{-6}$ for the field perpendicular to the C-axis.
$= 1.9 \times 10^{-6}$ for the field parallel to the C-axis.

The above equation summarizes measurements made from 200°C to 600°C.

At 8.5 Kmc/s. the loss tangent is less sensitive to temperature, and measurements made in the temperature range 20°C to 700°C can be represented within 10 per cent by

$\tan\delta = 2.8 \times 10^{-5} \times 10^{T/800}$ field perpendicular to the C-axis.
$= 8.5 \times 10^{-5} \times 10^{T/2000}$ field parallel to the C-axis.

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No anomalous values at lower temperature have been reported.

The material presented in this report is based on published and unpublished measurements of M. W. P. Strandberg, who made the ruby data available, A. R. Von Hippel, the Linde Company, Maletson, Murphy and Rodney (Journal Opt. Soc. Amer. **48** 72 1958), and Ballard, McCarthy and Wolfe (Report 2389-11-S Willow Run Lab., Univ. of Mich. Jan. 1959).